Tribology International 127 (2018) 489–499

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Elastohydrodynamic lubrication for the finite line contact under transient loading conditions

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ARTICLE INFO

Keywords:
Elastohydrodynamic lubrication
Finite line contacts
Transient loading
Finite elements

ABSTRACT

Research related to elastohydrodynamic lubrication (EHL) has led to improved performance and durability of machine elements where non-conformal contact geometries interact. Only a relatively small portion of the EHL literature has, however, dealt with the lubricating performance of finite line contacts under non-steady conditions, commonly found in many practical applications. The purpose of this work has thus been to further understand the behaviour of finite line EHL contacts under transient conditions by studying a finite length roller subjected to a time varying load using a full-system finite element approach. The transient load was shown to initiate oscillations in the system, governed by waves of lubricant moving through the contact, affecting both pressure and film thickness throughout the contact.

1. Introduction

Research related to elastohydrodynamic lubrication (EHL) is a branch of tribological science that has been extensively studied during the last seventy years [1] and has helped engineers and researchers to improve designs of machine elements where lubricated non-conformal geometries interact. The majority of research related to numerical simulation of EHL has been conducted under the assumption that steady state conditions apply. However, in reality, many machine elements operate under constantly changing conditions where changes in e.g. load, speed and contact geometry are influencing the lubricating conditions over time. Typical examples where transient, non-steady, EHL contacts can be found are e.g. in a roller bearing where rolling elements move through the loaded zone, a rotating cam in contact with a roller follower or a pair of contacting gear teeth.

The transient conditions related to the aforementioned examples can be referred to as system related time varying conditions, where, on the other hand, there are contact localised transient effects on a detailed contact scale, describing e.g. the surface roughness interaction and variation. The contact localised transient effects have been studied to a relatively great extent throughout the years [2,3] and are out of the scope for this work, which focuses on system related time varying conditions, meaning that surface roughness is not considered in this work.

EHL under non steady conditions was relatively early investigated by Christensen [4] who studied the flow between impacting bodies described not only by the pressure, but also by the squeeze of lubricant between the approaching bodies. The transient investigations were then further extended by e.g. Hook [5] and Larsson [6] to incorporate flow due to the pressure (Poiseuille flow), the entrainment (Couette flow) and also the squeeze while solving the EHL problem during time. Other studies focusing on vibrations in the contact due to transient loads have also been presented, where Wijnant [7] presented a methodology to numerically study the dynamics of ball bearings. This was achieved by the development of a model incorporating inertia of the moving bodies, which was shown to enable the study of oscillations in the lubricated system [8]. These oscillations were shown to give rise to effects that could not be studied assuming steady state conditions and was shown to have good correlation to experiments [9,10].

Nomenclature

a_x	Hertzian contact radius (m)	u_s	Sum velocity $(u_1 + u_2)$ (m/s)
a_V	Thermal expansivity, vol.-temp. $(°C^{-1})$	u_e	Entrainment speed $(u_s/2)$ (m/s)
B	Doolittle parameter	u, v, w	x-, y-, z-component of elastic def. (m)

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https://doi.org/10.1016/j.triboint.2018.06.035
Received 4 March 2018; Received in revised form 27 June 2018; Accepted 28 June 2018
Available online 30 June 2018

$\boldsymbol{C}$	Compliance matrix	U, V, W	X-, Y-, Z-component of elastic def. (−)
E	Modulus of elasticity (Pa)	$\boldsymbol{U_v}$	Displacement vector
E'	Reduced modulus of elasticity (Pa)	V	Volume of lubricant (m^3)
f	Applied load (N)	V_r	Volume at ref. state of lubricant (m^3)
f_i	Initial applied load (N)	x, y, z	Spatial coordinates (m)
f_f	Final load (N)	X, Y, Z	Dimensionless spatial coordinates
$\mathcal{F}$	Dimensionless load (−)	z_m	Crowning design parameter (m)
G	Dimensionless equivalent geometry (−)		
h	Film thickness (m)	β_K	Temperature coefficient of K_0 (K^{-1})
H	Dimensionless film thickness (−)	δ	Rigid body displacement (m)
h_e	Length of element	$\bar{\delta}$	Dimensionless deformation (−)
K_0	Isothermal bulk modulus, $p = 0$ (Pa)	Δ	Dimensionless rigid body disp. (−)
K_{00}	Isothermal bulk modulus at 0 K (Pa)	$\boldsymbol{\varepsilon}$	Strain tensor
K_0'	Rate of change of K_0 at $p = 0$	ε_c	Occupied vol. thermal expansivity (K^{-1})
K_1, K_2	Design parameters for crowning (−)	λ_L, μ_L	Lamé parameters (Pa)
L_1, L_2	Length of roller and ring respectively (m)	μ	Viscosity (Pas)
l	Order of stabilisation	μ_0	Viscosity at ambient pressure (Pas)
m	Mass in motion (kg)	$\bar{\mu}$	Dimensionless viscosity (−)
p	Pressure (Pa)	ν	Poisson's ratio (−)
p_h	Maximum Hertzian pressure (Pa)	Ω_n	Dimensionless natural frequency (−)
P	Dimensionless pressure (−)	ρ	Density (kg/m^3)
Pe	Local Peclet number in element	ρ_0	Density at ambient pressure (kg/m^3)
R_0	Occupied volume fraction at ref. state	$\bar{\rho}$	Dimensionless density (−)
R_x	Reduced radius in x-direction (m)	ρ_{AD}	Artificial diffusion tuning parameter
R_y	Reduced radius in y-direction (m)	$\boldsymbol{\sigma}$	Stress tensor
t	Time (s)	Θ	Dimensionless time (−)
T_r	Reference temperature (K)	Θ_f	Dimensionless end time of step load (−)
T_{oil}	Oil temperature (K)		

Furthermore, the EHL contact has traditionally been treated either as an infinite line contact (1D problem) or, elliptical- or point contact (2D problem). Historically important studies related to the infinite line contact include the works by e.g. Petrusevich [11], Dowson and Higginsson [12] and others, who laid the foundation of the EHL understanding and theoretical simulation based on Ertel and Grubin's [13,14] discovery of the influence on both deformation and rheology due to the relatively high contact pressure in the contact. Other historically important studies are e.g. the development of empirical formulas by Hamrock and Dowson [15], who published a series of papers that gave engineers tools to use for machine element design also for point- and elliptical contacts. Later, thanks to advances in numerical simulation in the form of the multigrid technique applied to EHL contacts by Lubrecht et al. [16] and further extended by Venner [17], detailed contact studies were enabled with relatively high efficiency.

Even though the understanding of the infinite line- and elliptical contacts has been well established, many of the aforementioned machine components are described by finite length EHL contacts. Thereby the analysis of the whole contact geometry becomes important and especially the edges, while optimising the lubricating performance for such applications. This is a topic that has not been studied to the same extent as the simpler geometries. However, an early investigation was made by Mostofi and Gohar [18] who simulated a cylindrical roller geometry and found that the minimum film thickness and maximum pressure were found near the edges of the roller. Their work was also later improved by Park and Kim [19] who obtained improved contour plots of the contact footprint itself. Detailed contact studies have been conducted for the finite line contact under steady state conditions by Zhu et al. [20] who also incorporated realistic geometries. However, the deformation was solved by using Boussinesq's solution, which is based on the infinite elastic half space approach and may therefore lead to a relatively large approximation of the deformation at the contact edge.

Habchi et al. [21] developed a full-system finite element (FE) approach to the EHL problem with focus on infinite line- and point contacts operating under steady-state conditions. This methodology led to further work being done by Shirzadegan et al. [22] in the field of steady state investigations of finite line contacts, where the edges could effectively be studied by the utilisation of classical elasticity theory and the use of a finite domain at which the EHL problem was solved. Their work has since then been further extended to analyse e.g. the influence of coatings for the finite line contact [23].

The literature does only cover to a very limited extent, to the authors' knowledge, the behaviour of finite line contacts subjected to transient loading conditions [24]. The understanding of film thickness and pressure variations in the lubricated system following the variation in operating condition therefore poses a natural next step in the understanding of the lubricated contact. In order to facilitate further optimisation and design of finite line EHL contacts found in a plethora of machine elements, the novelty of the present study is an increased understanding of the system response (film thickness, film pressure and sub-surface stress) of a finite line EHL contact under transient loading conditions by focusing on the effects arising due to a transient loading event. In addition, the modelling approach used to simulate the problem is comprehensively explained, which describes the modelling procedure used to simulate a non-conformal lubricated contact between a logarithmically crowned roller and ring subjected to a step increased load, which represents a case typically found in a roller bearing with impact loading. The investigation is split into two parts; where at first a basic understanding of the steady state solution is established, studying the film thickness footprint and the EHL characteristics throughout the contact, including the edge effects, while also comparing the finite line contact model to the infinite line approximation. Thereafter an investigation of the system response for the aforementioned transient load is presented, where oscillations initiated by the step load are studied, mainly with focus on what was seen to be fluctuations around the steady state value. The analysis highlights transient effects in the lubricated finite line EHL contact that become especially important to consider while analysing systems that are continuously subjected to transient loading conditions during operation.

2. Methodology

The methodology and model described in this section can be used to study finite length EHL contacts under transient conditions. In the model, the contact simulated represents the contact between a rolling